Development of a 7-Meter Inflatable Reflectarray Antenna

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This paper presents the structural and mechanical development of a 7-meter inflatable/self-rigidizable reflectarray antenna that is intended for space communication applications. Several structural schemes had been developed and a trade study was conducted. Top three schemes were identified and their deployment procedures were studied. Detailed design analysis for the most attractive scheme was performed. Dynamic characteristics of this scheme was also analyzed

Nomenclature

ω_1	=	first modal natural frequency
E	=	young modulus of elasticity
I	=	moment of inertia
L	=	length of the boom
K_1	=	parameter constant
ρ	=	density
A	=	cross sectional area

I. Introduction

This paper presents the structural and mechanical development of a 7-meter inflatable/self-rigidizable reflectarray antenna that is intended for space communication applications. The reflectarray antenna architecture employs the beam scanning and circular polarization technology that allows the use of a flat surface instead of a parabolic antenna surface. Structurally, a flat surface is comparatively easier to fabricate, package, and maintain than a curved parabolic surface.

This study started from several previously developed reflectarray antennas with smaller dimensions. The first reflectarray antenna technology demonstration model that used inflatable structures technology was a one-meter X-band reflectarray antenna[1]. The structure of this antenna is composed of an inflatable torus to hold the RF membrane and a hexagonal ring to hold the feed. The torus and the hexagonal ring are connected by three inflatable struts. The inflatable components of this antenna are made of Urethane-coated Kevlar, which requires keeping the pressure to maintain the rigidity of the structure during all the mission period.

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After the successful RF testing of the one-meter inflatable antenna, a three-meter technology demonstration model of the inflatable reflectarray at Ka-band was also developed[2, 3]. The configuration of this three-meter antenna is shaped like a horseshoe and its feed is supported by a hexagonal ring. The ring is connected by three asymmetrically located inflatable struts. Configuration was changed from circular to horseshoe to improve packaging such that, after the inflatable structure is deflated, the membrane and the deflated structure can be rolled up onto a rigid tube assembly without causing significant wrinkling to the membrane. The RF test results of the three-meter antenna demonstrated excellent radiation pattern characteristic. The three struts, hexagonal ring, as well as the horseshoe frame (excluding the rigid tube assembly) are all inflatable components made of Urethane coated Kevlar, which also need to be pressurized during the whole mission period.

It was gradually realized during the development process that space rigidization is essential for any future real space missions. Therefore, another scheme, named movie screen, was developed for the three-meter Ka-band inflatable reflectarray antenna[4-6]. The reflectarray surface of this scheme is deployed by two inflatable booms in a manner that is similar to the deployment of a movie screen. The inflation deployment process of the antenna only involves the unrolling and pressurization of two inflatable booms. This antenna employed an innovative inflatable/self-rigidizable boom technology, namely "Spring Tape Reinforced Aluminum Laminate Boom"[7]. A Spring Tape Reinforced Aluminum Laminate Boom automatically rigidizes after it is deployed by inflation pressure. The rigidization of this boom requires no space power, curing agent, or other added-on rigidization devices. Small damage caused by micrometeoroid impacts will not affect structural performance of the boom and inflation air is no longer needed after the boom is deployed.

II. Preliminary Scheme Development

The development of the 7-meter reflectarray antenna is the continuation of the aforementioned 3-meter reflectarray antenna. It started from the preliminary scheme development. Eight schemes were developed and they can be grouped into four categories: (1) Linearly Deployed Frame type; (2) Radially Deployed Umbrella type; (3) Revolutionary Deployment Disk type; (4) Folding Booms type. The following is a brief description of these eight schemes.

A. LDF with End-Supported and Singly Rolled Scheme:

This one belongs to Linearly Deployed Frame (LDF). The main idea of this concept is to keep one end of the reflectarray fixed while rolling up the other end. This concept is identical to the 3-meter reflectarray previously developed [1]. Figure 1 is a fully deployed CAD drawing of the LDF with end-supported and singly rolled design. This design requires two self-rigidizable inflatable booms.

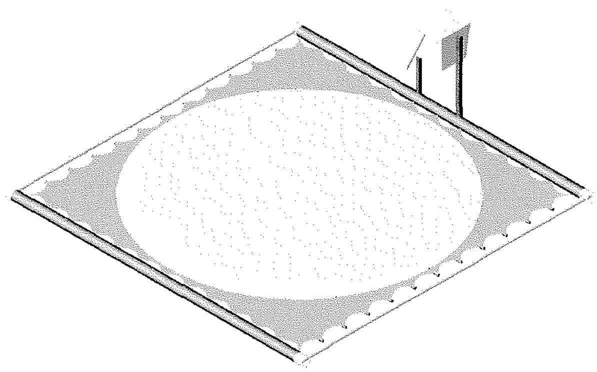

Figure 1. LDF with end supported and singly-rolled scheme

B. LDF with Mid-Span Supported and Doubly Rolled Scheme:

This one belongs to Linearly Deployed Frame (LDF). In this concept, a rigid support is placed in the middle of the antenna and is fixed while both ends roll out. Figure 2 is a fully deployed CAD drawing of the LDF with mid-span supported and doubly rolled design. This design uses four self-rigidizable inflatable booms.

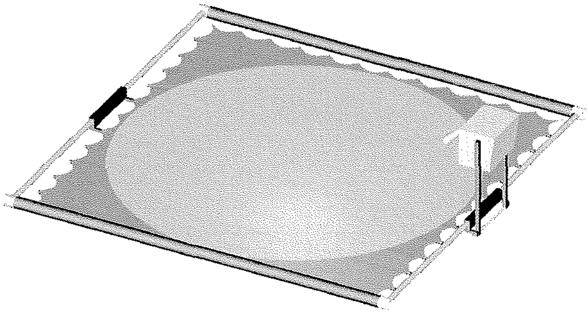

Figure 2. LDF with mid-span supported and doubly rolled scheme

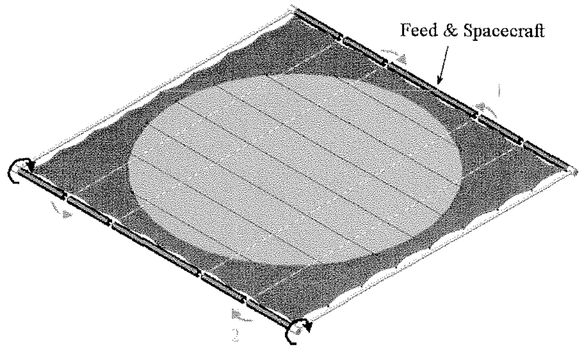

Figure 3. LDF with four folds and singly rolled scheme

C. LDF with Four Folds and Singly Rolled Scheme:

This one belongs to Linearly Deployed Frame (LDF). In this scheme, the entire antenna is folded along four folding lines as shown in Figure 3. During folding the four innermost hinges fold inwards first in the direction shown by the arrows labeled 1. Next the four outermost hinges fold outwards as shown by the arrows labeled 2. This design requires two self-rigidizable inflatable booms.

D. LDF with Two Folds and Singly Rolled Scheme:

This one also belongs to Linearly Deployed Frame (LDF). In this scheme, the entire antenna is folded along two folding lines as shown in Figure 4. During folding, the schemes folds into a Z-fold configuration first by folding in the direction shown by the arrow labeled 1. Next it folds in the direction shown by the arrow labeled 2. This design also requires two inflatable/self-rigidizable booms.

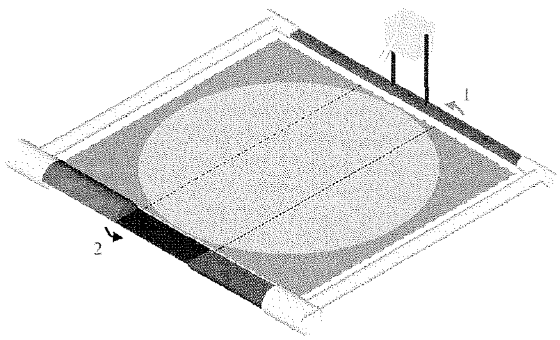

Figure 4. LDF with two folds and singly rolled scheme

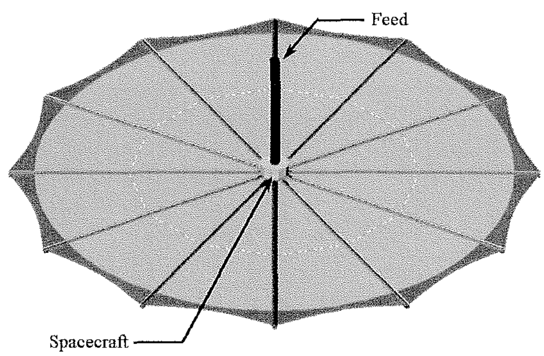

Figure 5. RDU unsupported scheme

E. RDU Unconnected:

This concept belongs to Radially Deployed Umbrella (RDU) category. The membrane packaging incorporates some of the similar features as in a common umbrella. The main idea of this concept is to have the booms deployed outwards from the center first. The membrane is then pulled out in a similar way as in an umbrella. Figure 5 illustrates a fully deployed CAD drawing of this concept. This concept requires the use of twelve self-rigidizable inflatable booms.

F. RDU with Cable Support:

This concept also belongs to Radially Deployed Umbrella (RUD) category. It is similar to the Unconnected RDU concept. The only difference is that this concept uses cables to connect all booms. The advantage of doing this is that it has much higher rigidity than the unconnected RDU. The disadvantage is that it increases the packaging and deployment complexity. Figure 6 is a CAD drawing representation of this scheme.

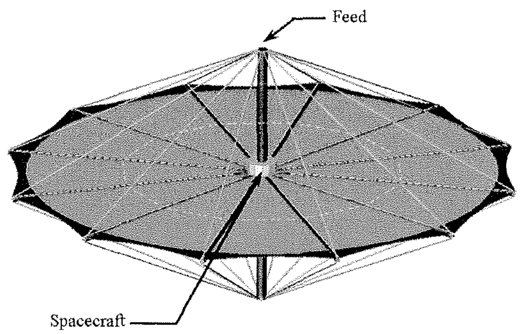

Figure 6. RDU with cable-supported scheme

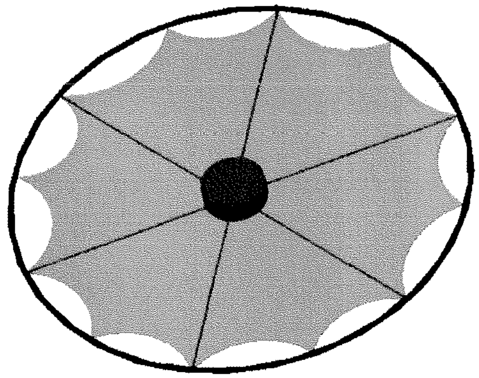

Figure 7. Revolution deployment disk scheme

G. Revolutionary Deployment Disk Antenna

This one belongs to Revolutionary Deployment Disk type. This concept incorporates six panels, each making up a portion of the reflect-array. From a stowed position the bottommost panel stays fixed while the remaining five panels rotate 60 degrees from the previous adjacent panel. Figure 7 is a CAD drawing representation of this scheme.

H. Folding Booms

This one belongs to Folding Booms type. This concept is a hollow shell that breaks into four sections during the deployment. Figure 8 shows a fully deployed CAD drawing of this antenna.

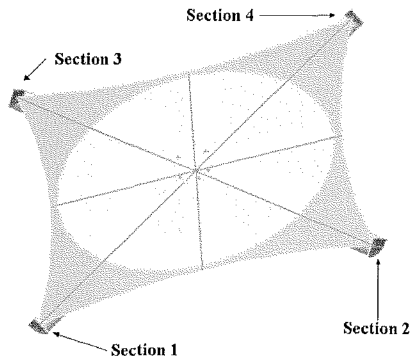

Figure 8. Folding booms scheme

III. Preliminary Trade Study

After the eight preliminary schemes were developed, a preliminary trade study was conducted to identify the most feasible ones for further developing. Twelve criteria were acquired for performing the trade study. These twelve criteria have ratings from 1 (the worst) to 10 (the best). Each criterion also has a weighting factor of 1 (the least important) to 3 (the most important). The twelve criteria are: 1) deployment reliability, 2) mass, 3) packaging efficiency, 4) launch vehicle compatibility, 5) design complexity, 6) ease of tensioning, 7) structural rigidity, 8) thermal distortion, 9) RF design compatibility, 10) ease of fabrication, 11) design heritage, and 12) feasibility of ground RF testing. Explanations on the criteria as well as the rationale behind assigning the weighting factors are given as following.

1) Deployment Reliability:

Lessons learnt from previous missions, more than seventy percent of mission fails are caused by unsuccessful deployments. Due to the innovativeness of the packaging and deployment of this antenna, deployment reliability is the most critical issue that needs to be investigated. The deployment reliability is determined by the complexity of the deployment process. If the deployment process is complex and uncertain, there is a higher probability for it to fail. Considering the importance of the deployment reliability, a weighting factor of 3 was assigned.

2) Mass:

The total mass of the system, including the membrane and the support structure, may determine the launch cost. Launch cost is a major portion of the total mission cost. The heavier the system, the more energy it takes to get it into space. This means a more powerful rocket will be needed. Higher cost will be resulted consequently. Even though the mass of the system is important, it is not critical to the success of the mission. Therefore a weighting factor of 2 was given to the mass consideration.

3) Packaging Efficiency:

The RF component of the antenna is a 7-meter diameter membrane reflectarray, which translates to an overall dimension of over 7 meters when the support structure is included. If the antenna can be efficiently packaged into a smaller launch vehicle fairing, the launch cost can be reduced. The possible drawback for a smaller package is the likelihood that more folding lines on the membrane may be introduced. This reduces the overall effectiveness of the reflectarray. Because of the relative importance in packaging efficiency, a weighting factor of 3 is assigned.

4) Launch Vehicle Compatibility:

This criterion addresses the compatibility between the packaged antenna and the launch vehicle. High packaging efficiency with bad launch vehicle compatibility may still end up requiring a large rocket to launch the antenna into space. Accordingly, it still inevitably correlates to an expensive launch. Since packaging efficiency has been assigned a weighting of 3 criteria, a weighting factor of 1 is assigned to this criterion.

5) Design Complexity:

Both the antenna development cost and the in-space deployment reliability are reasonably determined by the design complexity. The more components and sub-systems there are, the more development budget will be requested. On the other hand, more complex sub-systems and complicated technologies are employed, the unsuccessful in-space deployment possibility will be higher. Therefore, the design complexity has been given a weighting factor of 2.

6) Ease of Tensioning:

The performance of this antenna depends on the flatness of the membrane, which is determined by the membrane tensioning. After the antenna is deployed, uniform tensioning is required to stretch the membrane to be flat. In order to reliably apply the tension, we must take into consideration of how easily this can be accomplished for each design. Thus a weighting factor of 2 has been given.

7) Structural Rigidity:

The rigidity of the structure is crucial to the function of the antenna. This antenna is fairly large and flimsy, to minimize the structural vibration introduced by space maneuvering is a big challenge. It is desirable for this antenna to have its fundamental frequency as high as possible. A weighting factor of 2 has been provided to this category.

8) Thermal Distortion:

Space is considered to be a very hostile environment. This is because very high temperatures are experienced when the spacecraft is exposed to direct sunlight, and very low temperatures are expected in the absence of sunlight. These temperature extremes can distort the structure and destroy the structural precision. As a result, the antenna performance can possibly be degraded by thermal distortions. A weighting factor of 2 has been assigned the thermal distortion.

9) RF Design Compatibility:

The ultimate purpose to have a flat membrane surface is to accommodate RF patches. Performance of the antenna depends a lot on the membrane surface conditions of the reflectarray. If the scheme has excessive folding lines or has the alignment difficulties, the RF performance will be damaged. With this in mind, we are favorable to those schemes that are compatible with the RF design. Due to the high importance of this requirement, a weighting factor of 3 has been assigned.

10) Ease of Fabrication:

Considerations need to be given to the ease of the design and manufacturing of the antenna's components. Shells, booms, membranes, springs, and fasteners will be needed to construct the antenna. It is important to select a design for which these components can easily be acquired and the antenna can be easily assembled. A weighting factor of 2 is assigned.

11) Design Heritage:

The similarity between the proposed and the existing design is an important factor. It would make good sense to incorporate the aspects of the past designs that have been proven to work. Whether or not the proposed design can take advantage of such heritage is given a weighting factor of 1.

12) Feasibility of Ground RF Testing:

The final criterion concerns the testing of the RF performance on the ground. Due to the gravity, a supporting structure is always needed to hold and control the orientations of the antenna to accommodate the RF test. How easy it is to set up for ground testing needs to be of concern. Because the testing can be modified, a not too critical weighting factor of 1 was assigned.

An evaluation team was formed after these criteria had been finalized. A trade study was conducted and results are given by table 1. It can be seen from table 1 that the top three concepts are the LDF with Mid-Span Supported and Doubly Rolled scheme, the LDF with End Supported and Singly Rolled Scheme, and the LDF Two Folds and Singly Rolled Scheme.

Table 1. Trade study results

Trade aspects	Weighing factor	1	2	3	4	5	6	**7**	**8**
Deployment reliability	3	10	8	5	4	2	1	2	2
Mass	2	8	10	8	9	8	4	3	4
Packaging efficiency	3	5	5	9	9	7	6	4	6
Launch vehicle compatibility	1	5	5	10	10	8	7	5	7
Design complexity	2	10	9	7	6	3	1	3	5
Easy of tensioning	2	9	9	7	7	4	6	6	4
Structural rigidity	2	6	8	4	6	4	9	9	5
Thermal distortion	2	5	7	5	7	6	8	8	5
RF design compatibility	3	9	9	7	8	6	5	3	7
Easy of fabrication	2	9	7	5	4	4	3	3	3
Design heritage	1	9	9	7	7	4	4	2	4
Feasibility of ground RF testing	1	8	10	8	10	7	5	7	5
Weighted score		**189**	**192**	**163**	**172**	**127**	**120**	**112**	**121**
Ranking		2	1	4	3	5	7	8	6

1: LDF-- With End Supports & Singly Rolled Aperture
2: LDF-- With Mid-Span Supports & Doubly Rolled Aperture
3: LDF--Four Folds & Singly Rolled Aperture
4: LDF-- Two Folds & Singly Rolled Aperture
5: Radially Deployed Umbrella
6: Radially Deployed Umbrella--With Cable Supported
7: Revolution Deployment Disk Antenna
8: Folding Booms

IV. Deployment Processes of the Top Three Schemes

Basic considerations and deployment processes of the top three schemes are discussed as following.

The first concept is the LDF with Mid-Span Supported and Doubly Rolled Scheme and its deploying process is shown in Figures 9. The advantage of this scheme is that it uses four 3.6 meters long inflatable/self-rigidizable booms instead of two 7.65 meters long booms as used by other two schemes. Since the buckling capability of a long boom is inverse proportional to the square of the boom length, booms used by this scheme are much slimmer and lighter. The first step of the deployment process is the unrolling of four inflatable/self-rigidizable booms to unrolling the membrane in both sides as shown in Figures 9a to 9c. After that, the feed swings out from its stowed position to its functional position as shown in Figures 9d and 9e. The antenna is thus fully deployed.

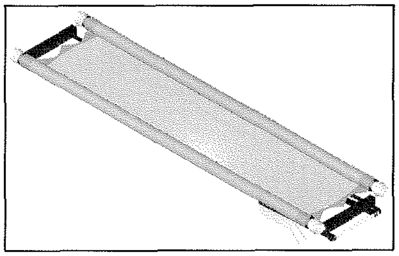

Figure 9a. Packaged antenna (LDF with Mid-Span Supported and Doubly Rolled Scheme)

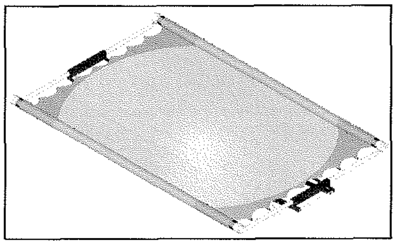

Figure 9b. Four inflatable/self-rigidizable booms and the membrane are unrolling

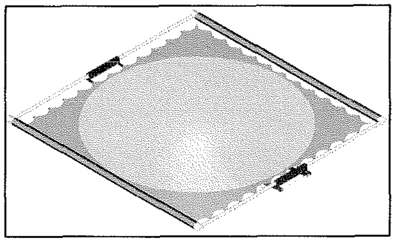

Figure 9c. Reflectarray is fully deployed

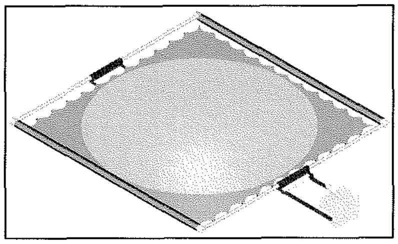

Figure 9d. Feed is deploying

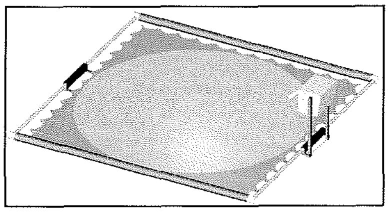

Figure 9e. Antenna is fully deployed

The second concept is the LDF with End-Supported and Singly Rolled Scheme. Compare to other schemes, this deployment process is the simplest one. The deployment process of this scheme is also identical to the fore developed Three-meter Reflectarray Antenna[6], which furnishes this scheme with high heritage and maturity. The deployment process of this scheme is very reliable since it only involves the unrolling of two inflatable/self-rigidizable booms. Figures 10 show the deployment process.

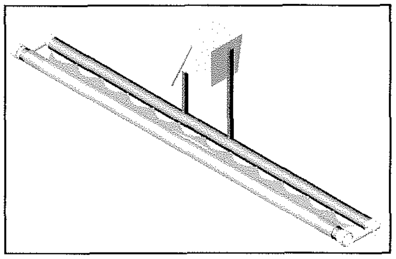

Figure 10a. Packaged antenna (LDF with End-Supported and Singly Rolled Scheme)

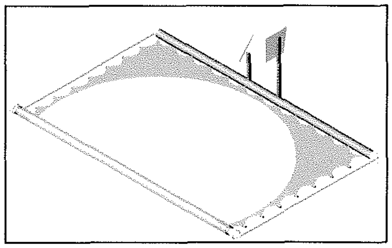

Figure 10b. Two inflatable/self-rigidizable booms and the membrane are unrolling

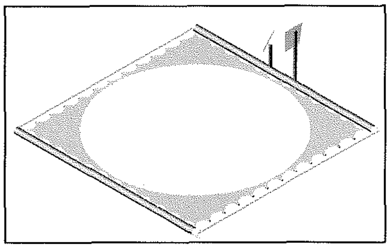

Figure 10c. Antenna is fully deployed

The third concept is LDF with Two Folds and Singly Rolled Scheme. The deployment process of this scheme is more complicated compare to aforementioned two schemes and requires more moving components for its deployment process. The attractiveness of this scheme is that it reduces the packaged length of the antenna from around 7.5 meters to around 2.6 meters, which makes it possible to use a much smaller launch vehicle than previously discussed two schemes. The deployment process is shown in Figures 11. The first step of the deployment is that the feed moves out of the way and two inflatable/self-rigidizable booms and the membrane starts to unrolling as shown in Figure 11b. After the booms are fully inflated, the membrane and tow end-bars start to unfold as shown in figure 11d.

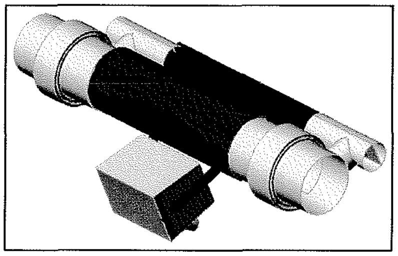

Figure 11a. Packaged antenna (LDF with Two Folds and Singly Rolled Scheme)

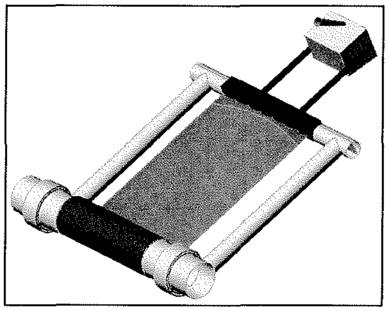

Figure 11b. Two inflatable/self-rigidizable booms and the membrane are unrolling after the feed is turned out of the way

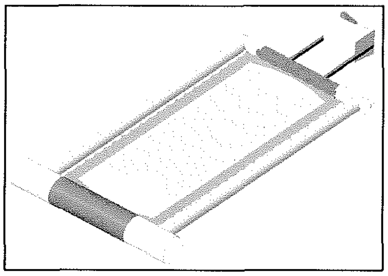

Figure 11c. Two inflatable/self-rigidizable booms are fully inflated

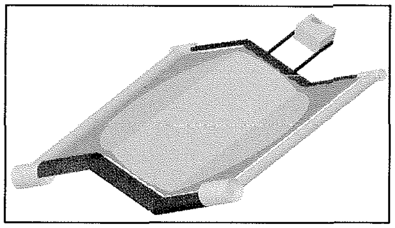

Figure 11d. The membrane and two end-bars are unfolding

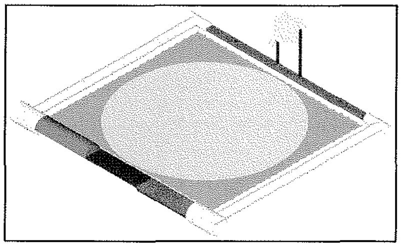

Figure 11e. The feed is turned to the final position and the antenna is fully deployed

V. Development of the LDF with Two Folds and Singly Rolled Scheme

Structural configurations and deployment procedures of both "LDF with Mid-Span Supported and Doubly Rolled Scheme" and "LDF with End-Supported and Singly Rolled Scheme" have been previously validated and demonstrated by the development of a 3-meter reflectarray antenna engineering model[4-6] and a 1-meter by 3-meter Inflatable Synthetic Aperture Radar[4]. The major challenge in developing the 7-meter unit is associated with the much larger aperture (over five times larger as compared to that of the 3-meter one). Such a large aperture can no longer be stowed in the fairings of a conventional launch vehicle, such as the DELTA II, without being folded up. As a result, the third scheme, "LDF with Two Folds and Singly Rolled Scheme" becomes the most attractive one. Due to aforementioned reasons, this study was then focused to the development of "LDF with Two Folds and Singly Rolled Scheme".

This development started from a preliminary design analysis. The thickness of the membrane is 5-mil and the membrane stress is required to be 90-psi. A trade study was performed by changing the numbers of catenary span and the catenary's heights[8]. A design point was determined thereafter. The parameters of this design point are: 1) there are 11 catenary spans along each side of the membrane; 2) the height of each span is 5.5-in; 3) the axial boom load induced by the membrane is 72.5-lbf; 4) the safety factor for the boom is 4. As a result, a boom that can withstand 290-lbf axial force needs to be developed.

The Spring Tape Reinforced (STR) aluminum laminate boom technology, which was originally developed for the three-meter reflectarray antenna[7], will be further developed to accommodate the seven-meter reflectarray antenna. Compared to other rigidization technologies, STR aluminum laminate boom automatically rigidizes after it is deployed with no space power, curing agent, or other rigidization system required. It is thus called self-rigidizable technology. A typical STR boom consists of a tube that is formed with aluminum laminate. Several spring tapes (also called blades) are attached to the inside wall of the tube in the axial direction. Spring rings are also placed periodically along the axial direction to reinforce the boom. With a wall thickness around 0.1 mm, a STR boom can be easily flattened, rolled-up (or folded-up), and inflation deployed by a very low pressure. The buckling capability of a STR aluminum laminate boom is very high mainly due to the high modulus of elasticity and curved cross-sectional profile of the spring tapes. It should be pointed out that spring tapes are very effective in resisting inward buckling and the aluminum laminate tube is very stable in resisting outward buckling. Therefore, these two components effectively complement each other in resisting local crippling of the boom. The buckling capability of a STR aluminum laminate boom can be scaled up by increasing the diameter of the tube and adding more spring tapes. In order to determine the ideal inflatable boom, several 10-meter long boom designs were modeled and analyzed using NASTRAN. Table 2 contains the specification of each boom along with the analyzed results.

Table 2. Results of the boom analyses

	Diameter (inches)	# of blades (width)	# of rings (width)	Weight (lb)	Buckling load (lb)
1	6.5	8 (1 in)	18 (1 in)	7.9	103.4
2	8	8 (1 in)	18 (1 in)	8.8	161.3
3	8	10 (1 in)	18 (1 in)	9.8	169.5
4	9.5	10 (1 in)	18 (1 in)	10.7	281.9
5	9.5	10 (1 in)	19 (0.5 in)	9.7	278.4
6	9.5	10 (1 in)	18 (1 in)	9.6	163.6
7	9.5	10 (1 in)	20 (1 in)	9.8	193.8
8	13	4 (4.3 in)	None	13.6	383.1
9	13	8 (2 in)	None	12.9	335.5

Following are some conditions and parameters for the boom analyses:

- The length of every boom is 10-meter. The boundary conditions are fix-free.
- The aluminum laminate of #7 and #8 is 2-mil aluminum with 1-mil polyester on both sides. The aluminum of other booms is 3-mil aluminum with 1-mil polyester on both sides.

Boom # 5 is identified to be the baseline design. It can take 278 lb when it is 10-m long. Assume Euler buckle, this boom can take 475 lb ($278.4 \times 10^2/7.652^2=475$) if it is 7.652-m long (7.652 m is the designed boom length of the 7-m antenna). The design of the baseline boom is a 9.5-inch diameter boom with 10 blades and 19 equally spaced rings. Figure 12 is an isometric view of the base line design. The total weight of the boom and the critical buckling capability were calculated to be 9.7 lb and 278.4 lb respectively. The mode shape of the buckling result of the base line design is shown on figure 13. Also the first three frequencies were analyzed to be 1.889 Hz, 1.889 Hz and 7.834 Hz and their corresponding mode shape are shown in figures 14-16.

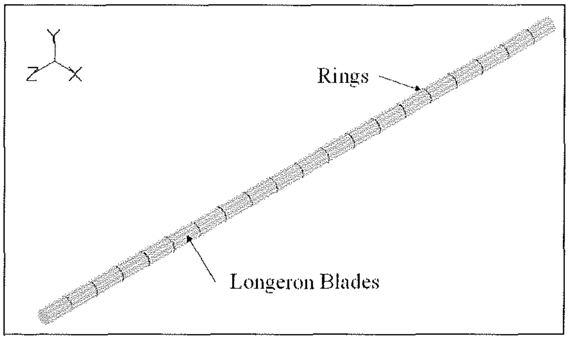

Figure 12. Isometric view of the baseline design

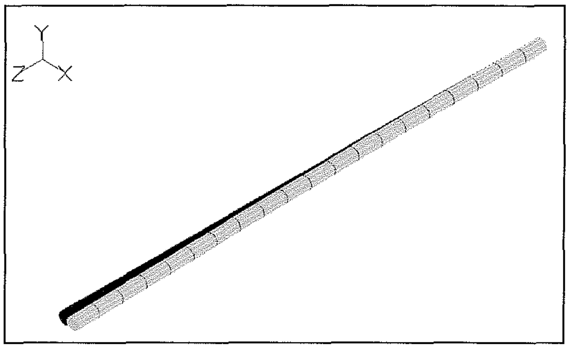

Figure 13. Buckling mode of the baseline design

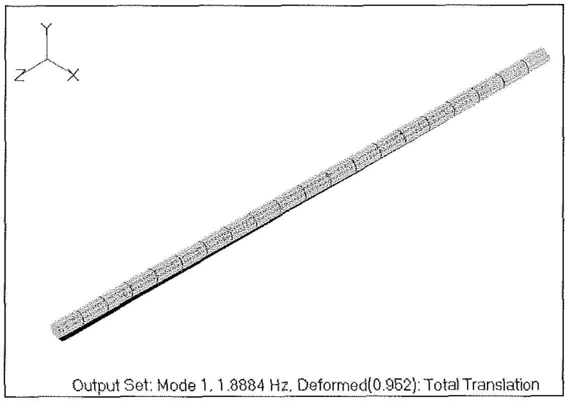

Figure 14. First modal frequency

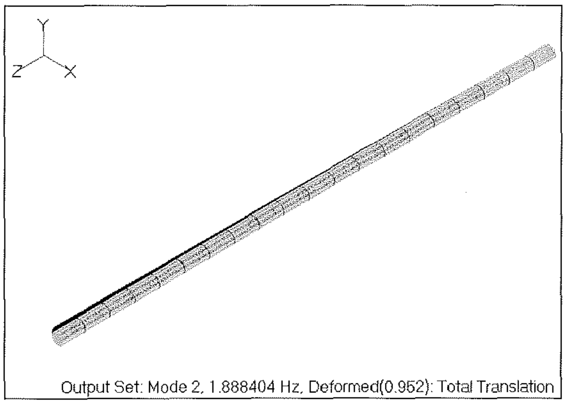

Figure 15. Second modal frequency

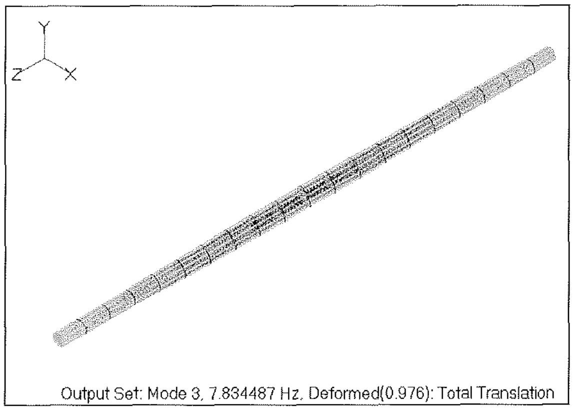

Figure 16. Third modal frequency

Form the first modal frequency, the equivalent bending stiffness of the baseline boom is calculated by:

$$EI = \left(\frac{\omega_1 L^2}{1.875^2} \right)^2 \rho A \tag{1}$$

The equivalent bending stiffness is calculated to be 5.02×10^4 N-m^2 and is used afterward to make a FEM model for the antenna dynamic analysis.

The structure of the antenna is very large and flimsy. The dynamic characteristics of the inflatable/self-rigidizable structure needs to be studied. A finite element model has been constructed and the modal analysis has been conducted. The membrane itself has very little out-of-plane bending stiffness. The out-of-plane stiffness comes from pretensioning. It is the function of the membrane stress distribution and is called differential stiffness. Therefore, the dynamic analysis of a membrane structure has two steps. The first step is the static analysis to obtain the stress distribution and the second step is the modal analysis. A finite element model with 379 nodes and 495 elements was assembled. The finite element software NASTRAN was used for the analysis. First, static analysis was performed to simulate the tensioning of the membrane and to obtain the differential stiffness resulting from this pretension. Modal analysis,

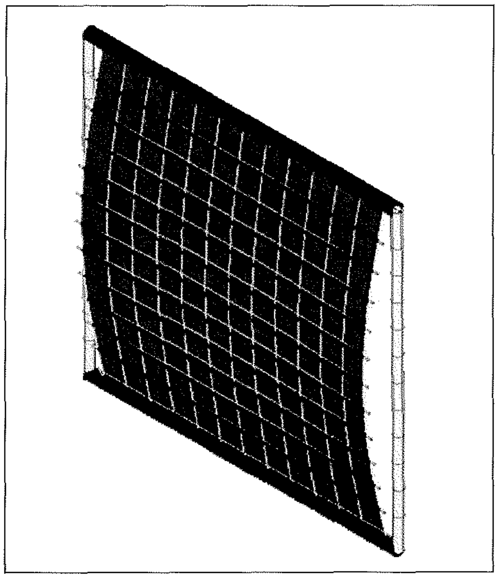

Figure 17. First mode shape (1.01 Hz)

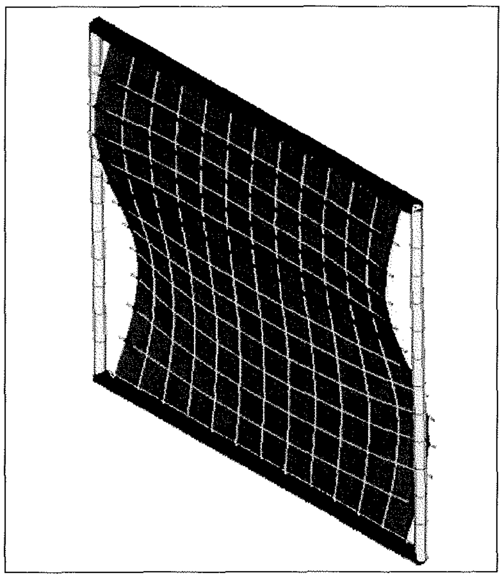

Figure 18. Second mode shape (1.86 Hz)

incorporating differential stiffness induced by pretension of the membrane, was performed consequently. Figures 17 to 19 are the first three mode shapes of the antenna.

The first frequency is analyzed to be 1.01 Hz, which is higher than the frequency requirement. It is concluded that current antenna design is feasible for further development.

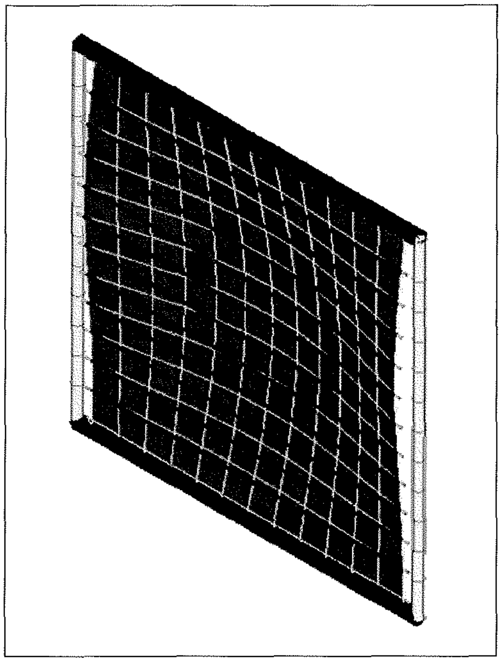

Figure 19. Third mode shape (2.05 Hz)

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